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Yu et al.

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(54) **METHOD OF MANUFACTURING AN EXTREME ULTRAVIOLET (EUV) MASK AND THE MASK MANUFACTURED THEREFROM**

(71) Applicant: **Taiwan Semiconductor Manufacturing Co., Ltd.**, Hsinchu (TW)

(72) Inventors: **Chia-Hao Yu**, Hsinchu (TW); **Ming-Yun Chen**, Hsinchu (TW)

(73) Assignee: **TAIWAN SEMICONDUCTOR MANUFACTURING CO., LTD.**, Hsinchu (TW)

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G03F 1/72 (2012.01)
G03F 1/22 (2012.01)

(52) **U.S. Cl.**
CPC ... ***G03F 1/72*** (2013.01); ***G03F 1/22*** (2013.01)

(58) **Field of Classification Search**
CPC G03F 1/72; G03F 1/22
USPC 430/5
See application file for complete search history.

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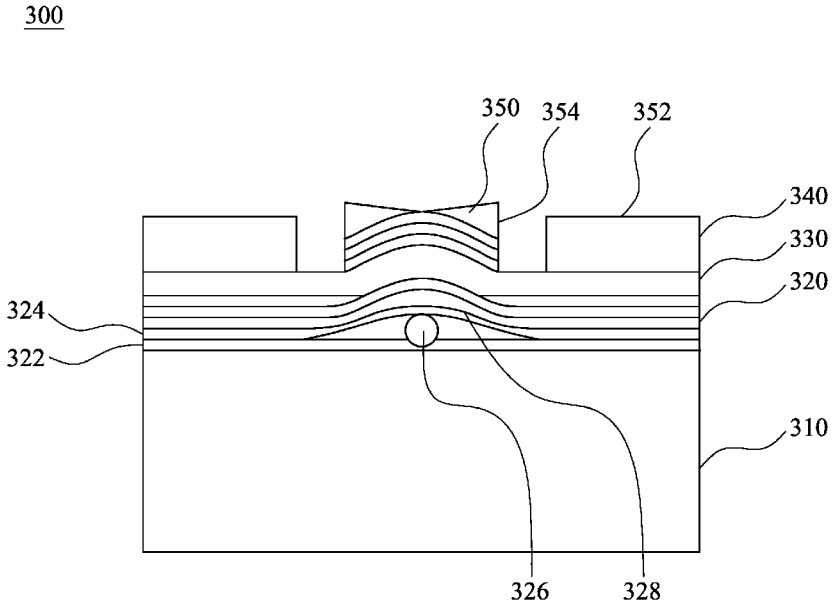
Primary Examiner — Stephen Rosasco
(74) *Attorney, Agent, or Firm* — Maschoff Brennan

(57) **ABSTRACT**

Any defects in the reflective multilayer coating or absorber layer of an EUV mask are problematic in transferring a pattern of the EUV mask to a wafer since they produce errors in integrated circuit patterns on the wafer. In this regard, a method of manufacturing an EUV mask is provided according to various embodiments of the present disclosure. To repair the defect, a columnar reflector, which acts as a Bragg reflector, is deposited according to various embodiments so as to locally compensate and repair the defect. According to the embodiments of the present disclosure, the reflective loss due to the defect can be compensated and recover the phase different due to the defect from, so as to form a desirable wafer printed image.

20 Claims, 12 Drawing Sheets



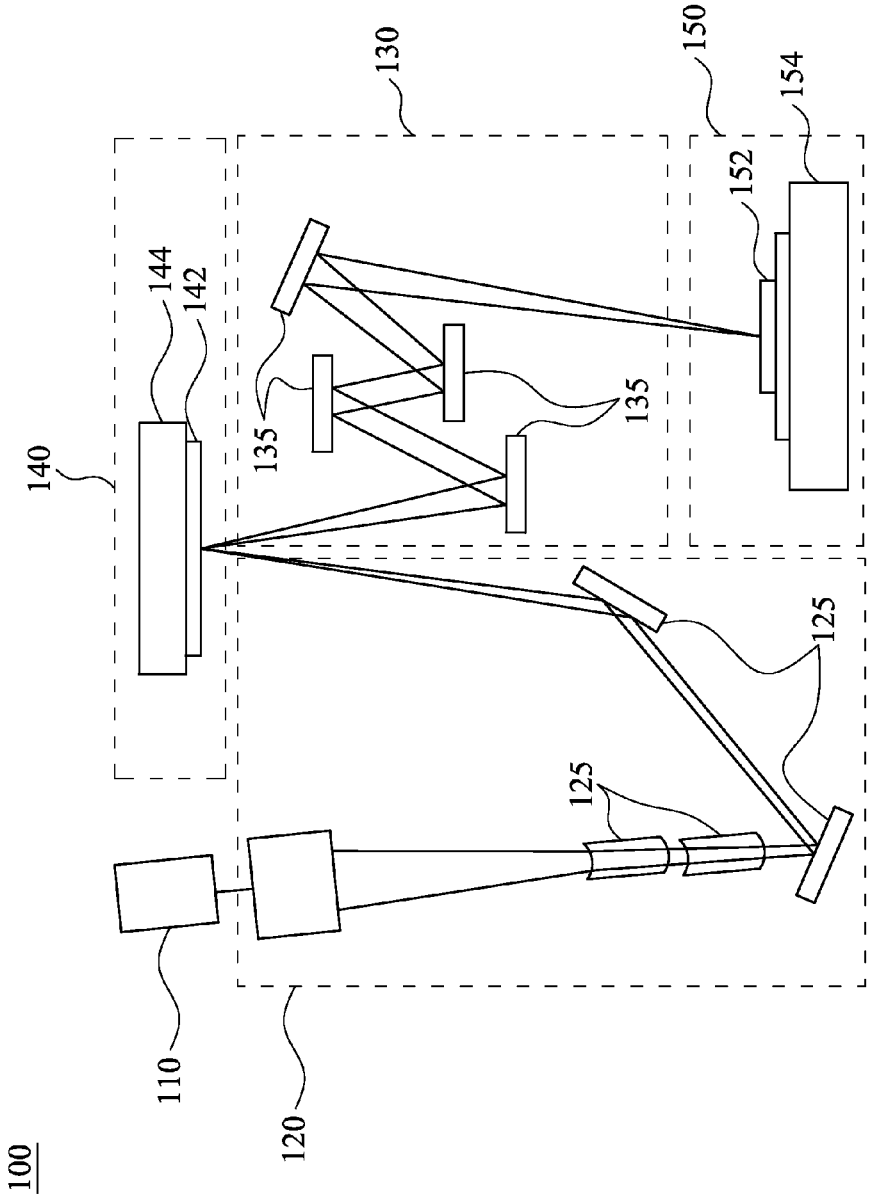


FIG. 1

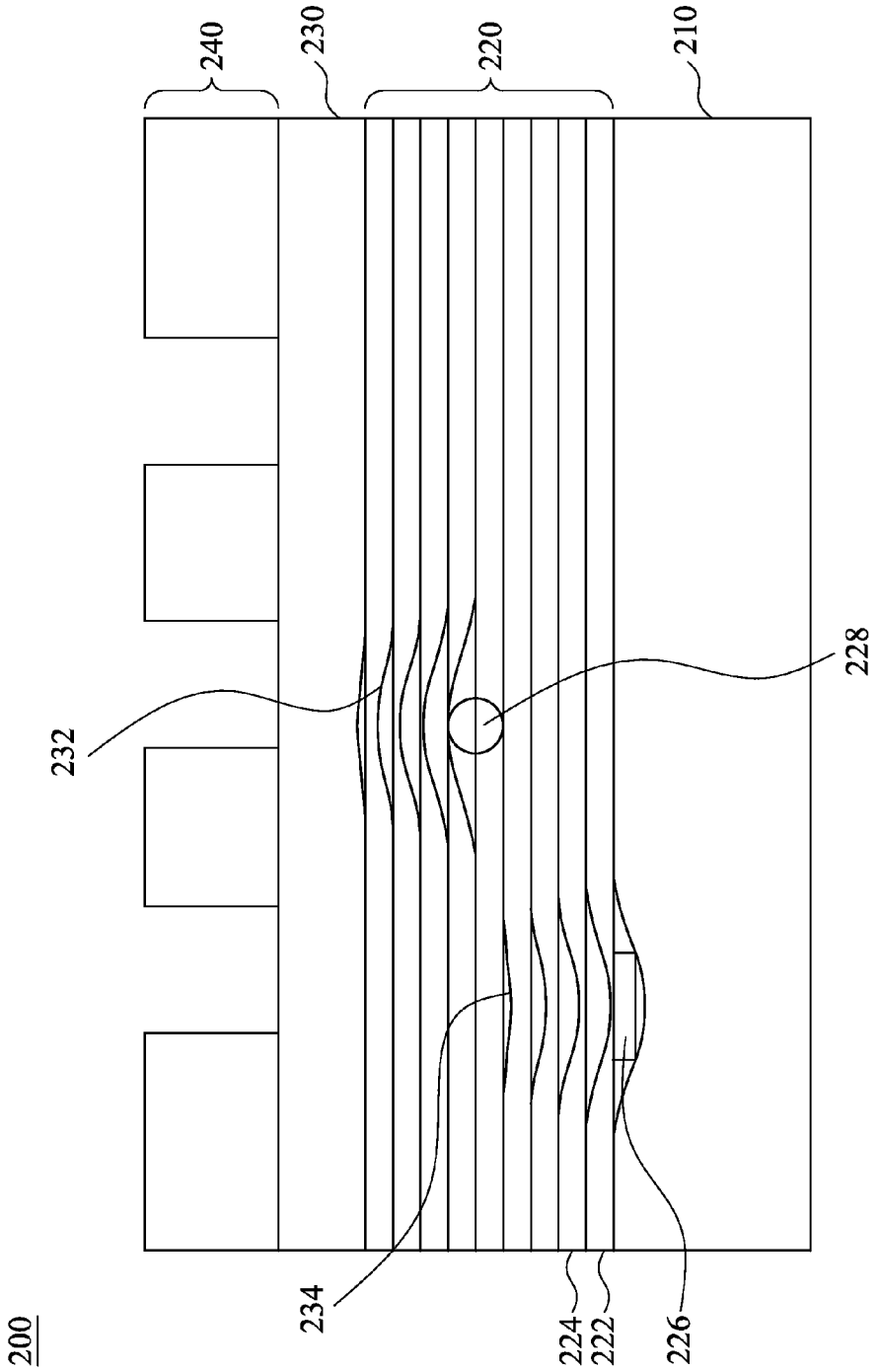


FIG. 2

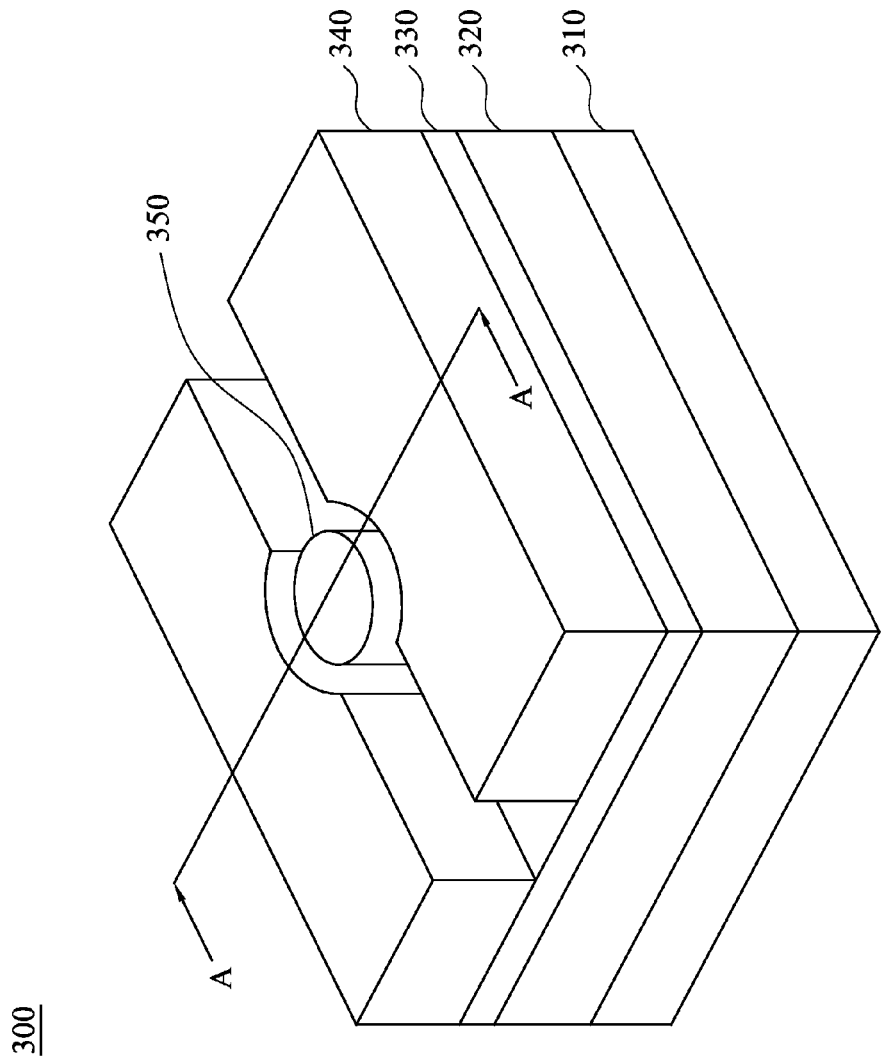


FIG. 3A

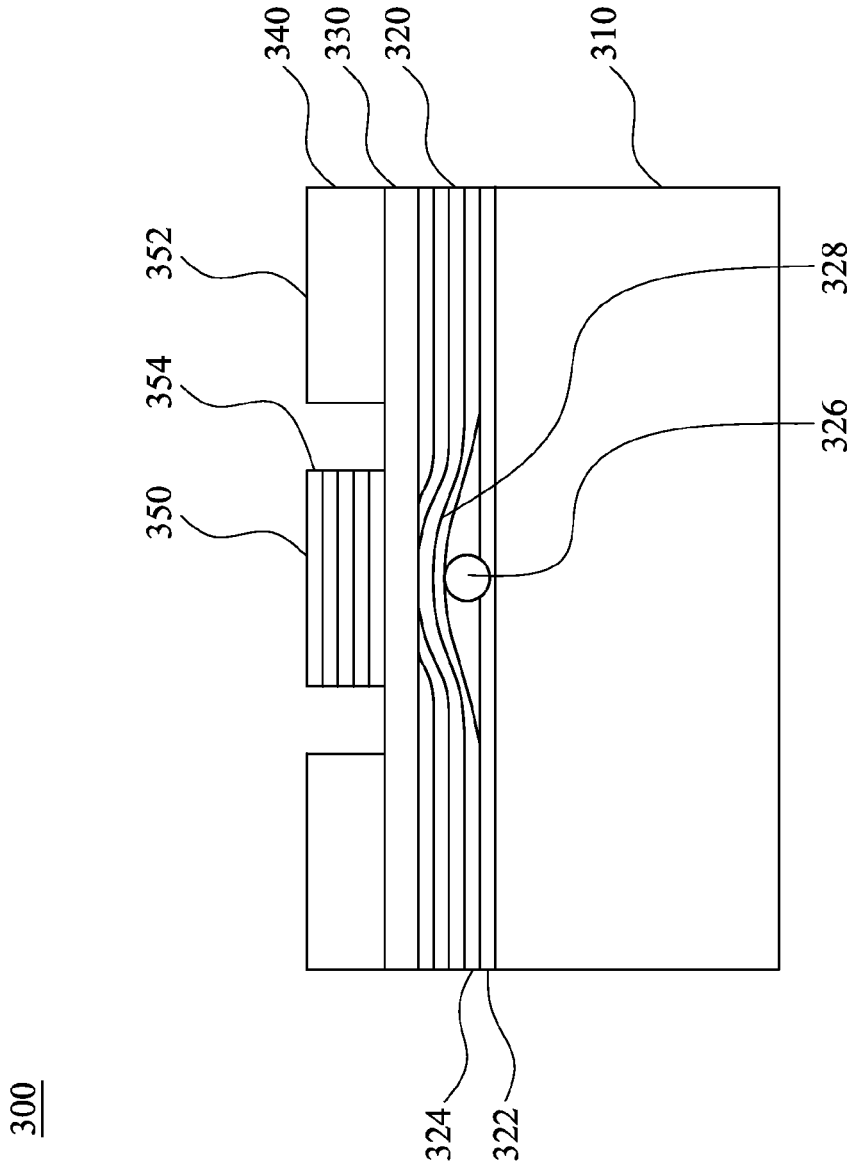


FIG. 3B

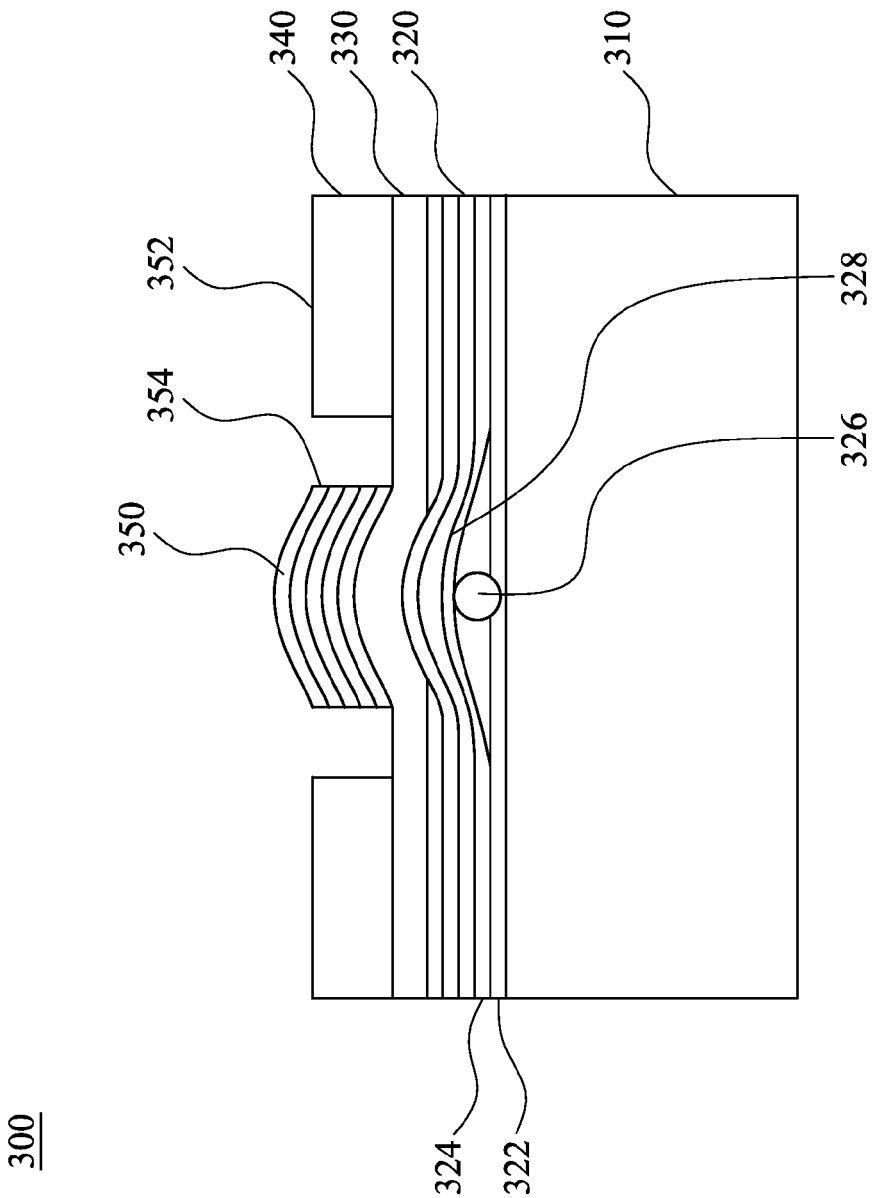


FIG. 3C

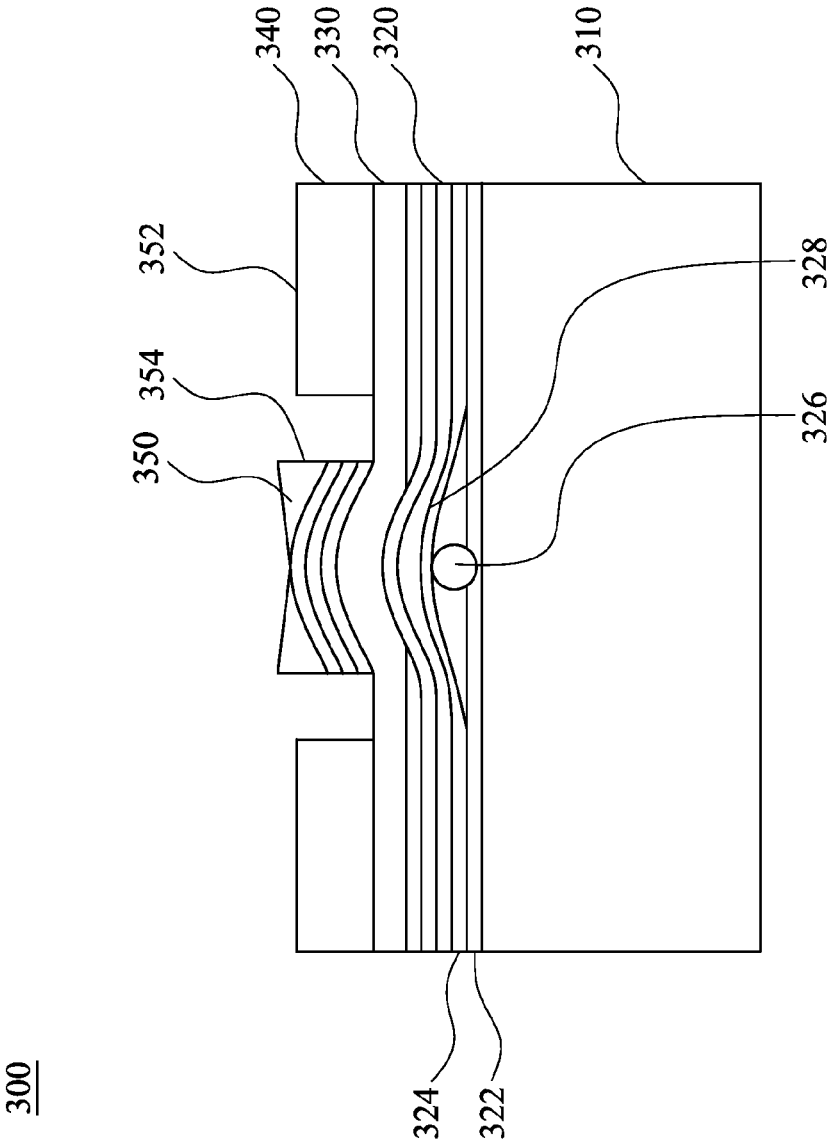


FIG. 3D

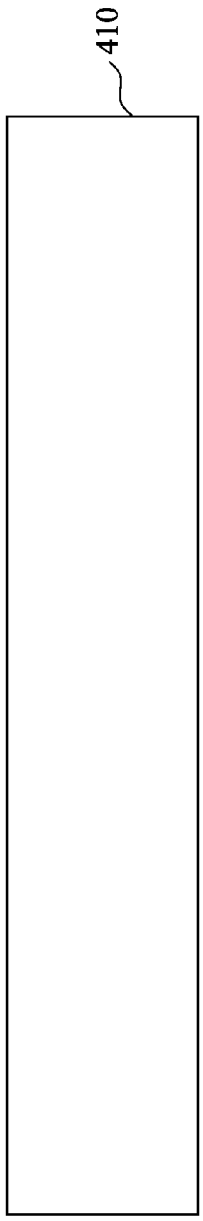


FIG. 4A

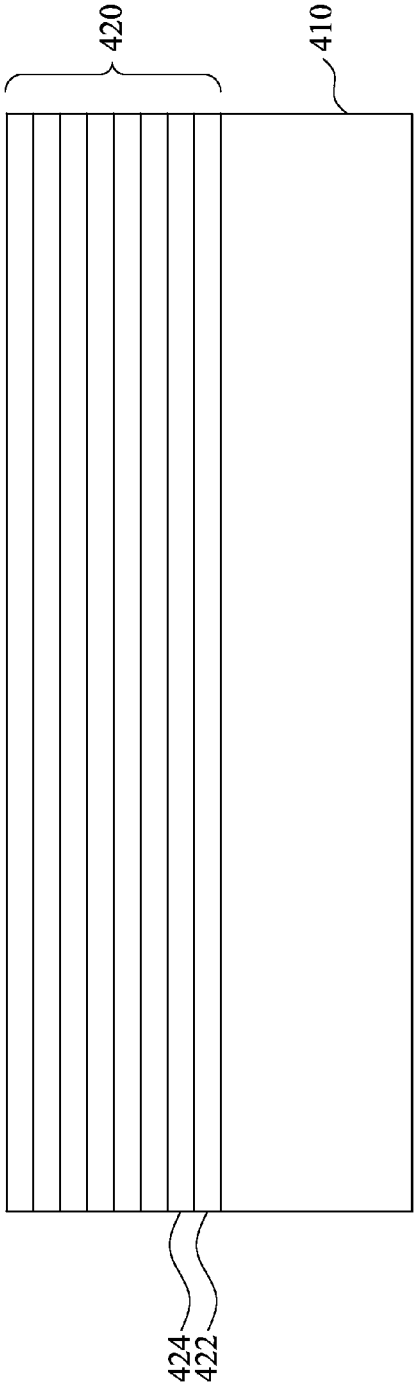


FIG. 4B

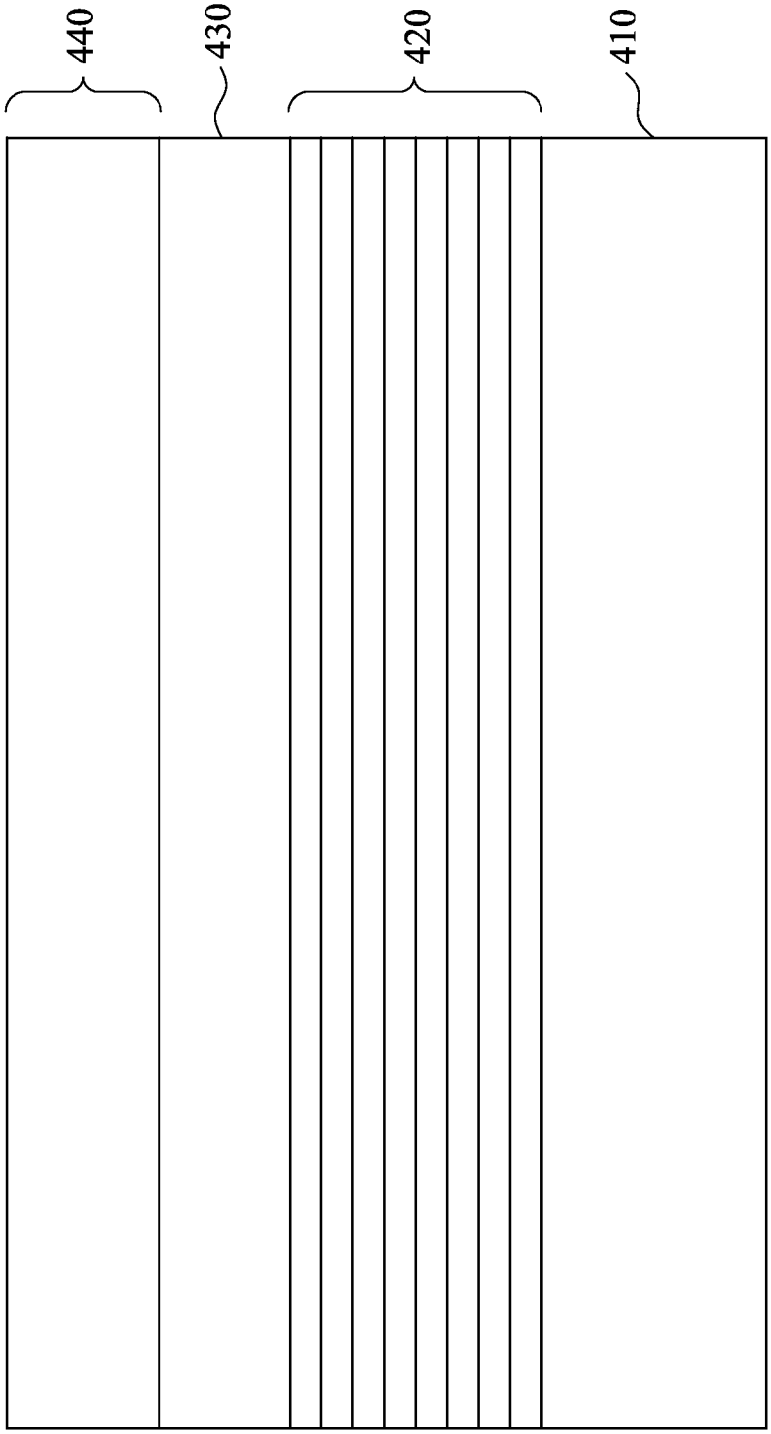


FIG. 4C

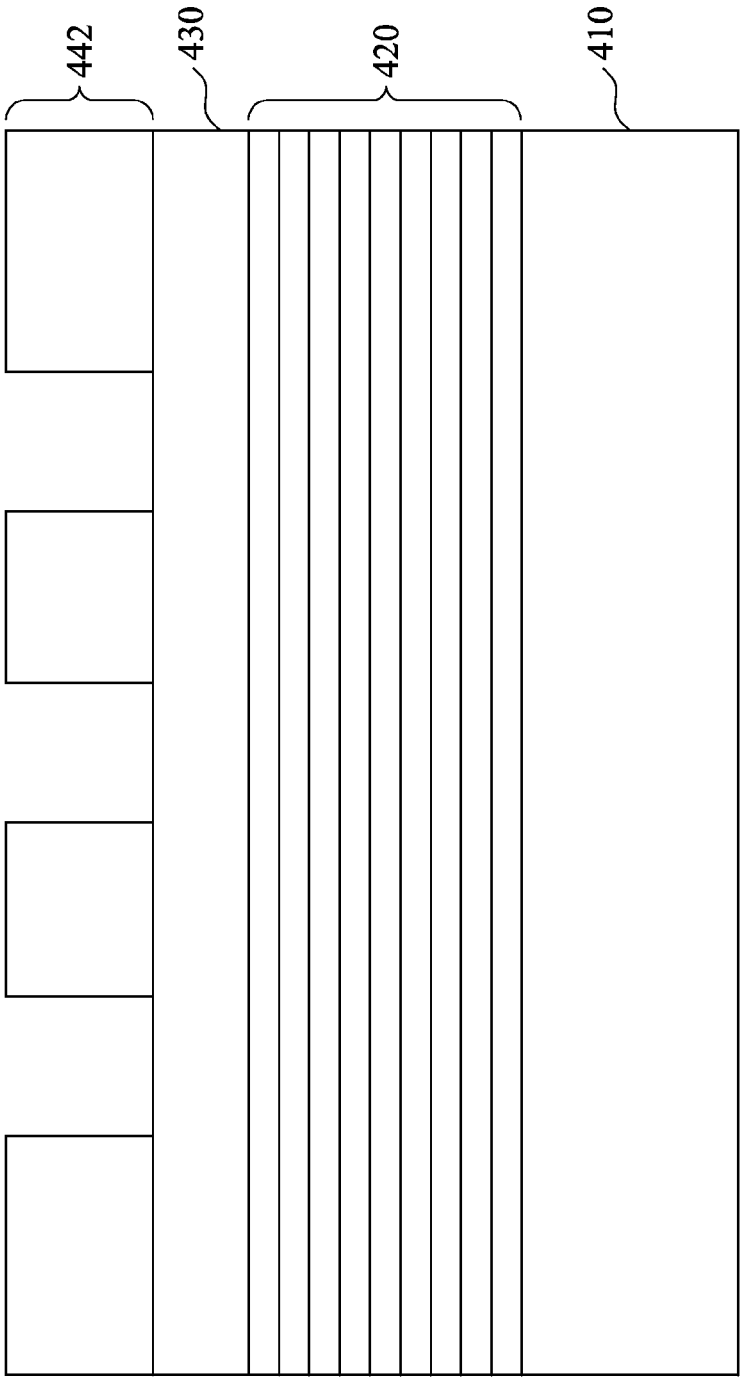


FIG. 4D

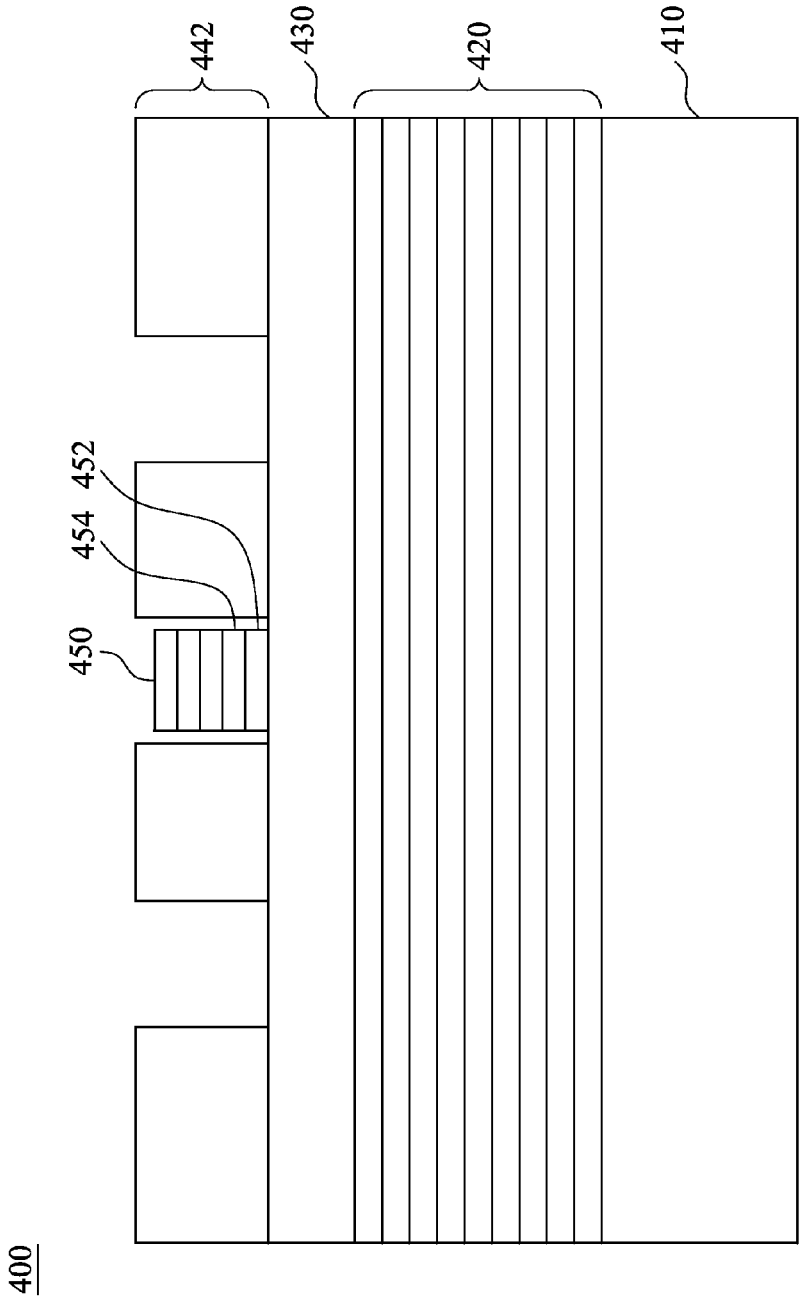


FIG. 4E

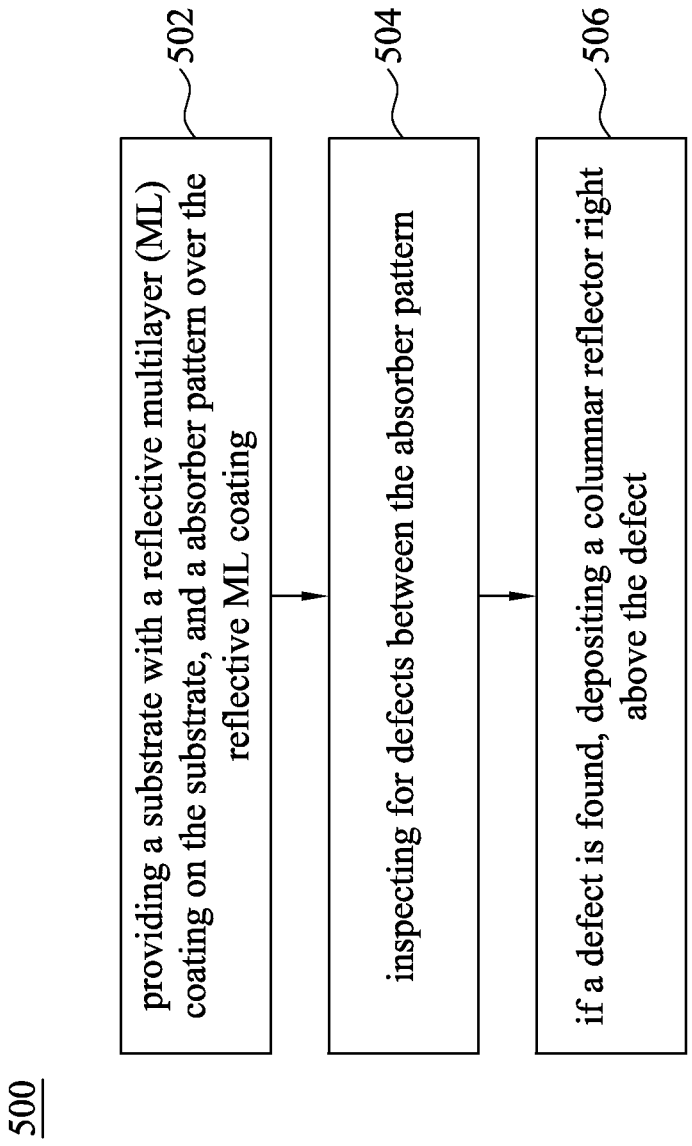

500
502
providing a substrate with a reflective multilayer (ML) coating on the substrate, and a absorber pattern over the reflective ML coating
504
inspecting for defects between the absorber pattern
506
if a defect is found, depositing a columnar reflector right above the defect

FIG. 5

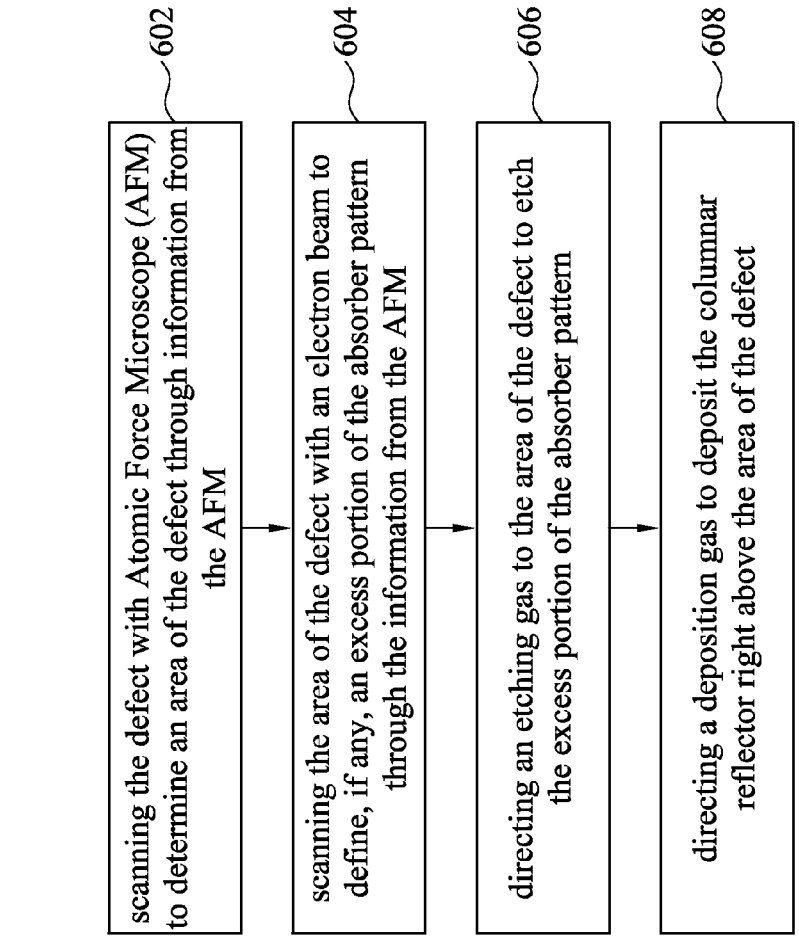

506
scanning the defect with Atomic Force Microscope (AFM) to determine an area of the defect through information from the AFM
602
scanning the area of the defect with an electron beam to define, if any, an excess portion of the absorber pattern through the information from the AFM
604
directing an etching gas to the area of the defect to etch the excess portion of the absorber pattern
606
directing a deposition gas to deposit the columnar reflector right above the area of the defect
608

FIG. 6

METHOD OF MANUFACTURING AN EXTREME ULTRAVIOLET (EUV) MASK AND THE MASK MANUFACTURED THEREFROM

BACKGROUND

Semiconductor devices have been more and more miniaturized. The semiconductor devices are mass-produced by repeatedly applying a photolithography process to form different layers of material. In a photolithography process, a photomask having a pattern is irradiated with light to transfer the pattern onto a photosensitive coating on a semiconductor substrate (hereinafter, referred to as "wafer") via a reduction optical system. To improve photolithography resolution so smaller features can be patterned, the exposure wavelength of optical lithography have been shortened. In recent years, photolithography that uses extreme ultraviolet (EUV) light (wavelength=13.5 nm) having a much shorter wavelength has been in development. However, at short wavelengths for EUV lithography, the electromagnetic radiation is absorbed by most materials, including glass used for conventional lenses and masks. Therefore a completely different tool is necessary for performing EUV lithography compared to conventional photolithography.

Some EUV lithography tools employ reflection type photomasks. A reflective EUV lithography mask (hereinafter, referred to as EUV mask) is composed of a reflective multilayer (ML) coating of alternatively stacked films of, for example, molybdenum (Mo) films and silicon (Si) films. The films are deposited on low thermal expansion material (LTEM) such as a quartz substrate or low-thermal-expansion glass substrate. An absorber pattern is formed on the reflective ML coating. The multilayer film is a thin film mirror that reflects light through constructive interference.

Because of the extremely short exposure wavelength of 13.5 nm, a small perturbation in the surface of the dielectric mirror can cause a phase defect in the reflection that can blur the pattern transferred onto a wafer. Some phase defects are caused by pits created during substrate polishing. Some phase defects are caused by particles on a substrate that are not removed by cleaning Improvements in structures of and methods of forming EUV masks that reflect with little or no phase defects continue to be sought.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is emphasized that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

FIG. **1** is a block diagram of a photolithography imaging system that uses a mask in processing a wafer.

FIG. **2** is a schematic cross-sectional view of an EUV mask in the existence of defects.

FIG. **3**A is prospective view schematically illustrating an EUV mask having a columnar reflector thereon according to various embodiments of the present disclosure.

FIG. **3**B is a schematic cross-sectional view of the EUV mask of FIG. **3**A along line AA.

FIG. **3**C is a schematic cross-sectional view of the EUV mask according to alternative embodiments of FIG. **3**B.

FIG. **3**D is a schematic cross-sectional view of the EUV mask according to alternative embodiments of FIG. **3**B.

FIGS. **4**A-E are schematic cross-sectional views at various stages of fabricating an EUV mask according to various embodiments of the present disclosure.

FIG. **5** a flowchart illustrating a method of fabricating an EUV mask according to various embodiments of the present disclosure.

FIG. **6** a flowchart illustrating an operation of depositing a columnar reflector in the method of fabricating an EUV mask according to various embodiments of the present disclosure.

DETAILED DESCRIPTION

It is to be understood that the following disclosure provides many different embodiments, or examples, for implementing different features of the invention. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. Moreover, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed interposing the first and second features, such that the first and second features may not be in direct contact. Various features may be arbitrarily drawn in different scales for the sake of simplicity and clarity.

The singular forms "a," "an" and "the" used herein include plural referents unless the context clearly dictates otherwise. Therefore, reference to, for example, a gate stack includes embodiments having two or more such gate stacks, unless the context clearly indicates otherwise. Reference throughout this specification to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the present disclosure. Therefore, the appearances of the phrases "in one embodiment" or "in an embodiment" in various places throughout this specification are not necessarily all referring to the same embodiment. Further, the particular features, structures, or characteristics may be combined in any suitable manner in one or more embodiments. It should be appreciated that the following figures are not drawn to scale; rather, these figures are intended for illustration.

An EUV mask composes of an absorber pattern layer and multiple layers of molybdenum and silicon to create the reflective type mask. The defect causing EUV phase shift are buried in reflective multilayer coating or on the substrate. Any defects in the reflective multilayer coating or the substrate of the EUV mask are problematic in transferring a pattern of the EUV mask to a wafer since they produce errors in integrated circuit patterns on the wafer. The phase defect changes the reflection angle and alters the thicknesses of the reflective layers, resulting in the reflection shifting from a designed maximum reflection. As result, the phase defect can reduce the intensity of the reflected EUV radiation, and shift the phase of the EUV radiation. As such, unexposed photoresist becomes residues, which deteriorates a desired wafer image for printing.

In order to compensate the EUV phase defect, a columnar reflector, which acts as a Bragg reflector, is deposited according to various embodiments to locally compensate and repair the EUV phase defect. According to the embodiments of the present disclosure, the reflective loss due to the EUV phase defect can be compensated and phase shift recovered, so as to reduce the deleterious effects of the defect on the wafer printed image.

In FIG. **1**, an EUV lithography imaging system **100** transfers a pattern of an EUV mask to a wafer. The system **100** includes a radiation source **110**, a condenser optics section **120**, a projection optics section **130**, a mask stage **140**, and a wafer stage **150**. The radiation source **110** may be any source able to produce radiation in the EUV wavelength range. One example of a suitable radiation source **110** is a plasma created when a laser illuminates a gas, such as a supersonic jet of xenon gas. As another example, a suitable radiation source **110** may be formed using bending magnets and undulators associated with synchrotrons. As a further example, a suitable radiation source **110** may be formed or developed from discharge sources, which have the potential to provide adequate power in the desired wavelength range. EUV radiation is strongly absorbed in virtually all transmissive materials, including gases and glasses. To minimize unwanted absorption, EUV imaging is carried out in near vacuum.

The mask stage **140** includes a transport stage **144** that scans a mask **142**. In the EUV lithography imaging system **100**, the mask **142** is reflective because EUV radiation is strongly absorbed in most materials such as transmissive photomasks that are used in traditional photolithography imaging systems.

The projection optics section **130** reduces the image from the mask **140** in the mask stage **140** and forms the image onto wafer **152** in the wafer stage **150**. In the EUV lithography imaging system **100**, the projection optics are reflective because of the absorption associated with EUV radiation. Accordingly, the projection optics section **130** includes reflectors or mirrors **135** that project radiation reflected from the mask **140** onto the wafer. The reflectance spectrum of the mask **142** may be matched to that of the mirrors in the projection optics section **130**. The term "projection optics" used herein should be broadly interpreted as encompassing any type of projection system, including refractive, reflective, catadioptric, magnetic, electromagnetic and electrostatic optical systems, or any combination thereof, as appropriate for the exposure radiation being used.

The wafer stage **150** includes a transport stage **156** that scans a semiconductor wafer **152** in synchrony with the mask **142** and steps the wafer **152** into a position to accept a next image from the mask **142**. During operation, a semiconductor wafer **152** mounted to the transport stage **154**. The projection optics impart the radiation light with a pattern in its cross-section to create a pattern in a target portion of the wafer **152**. It should be noted that the pattern imparted to the radiation light may not exactly correspond to the desired pattern in the target portion of the wafer, for example if the pattern includes phase-shifting features or shadows. Generally, the pattern imparted to the radiation light will correspond to a particular functional layer in a device being created in a target portion of the wafer **152**, such as an IC.

FIG. **2** is a schematic cross-sectional view of an EUV mask **200** with defects. The EUV mask **200** includes a substrate **210**, a reflective multiplayer (ML) film **220**, a buffer or capping layer **230**, and a patterned absorber layer **240**. In general, the reflective ML film **220** consists of 40 pairs of molybdenum (Mo) layer **222** and amorphous silicon (Si) layer **224**. The thickness of the individual layer of the reflective ML film **220** are about 3 and 4 nm for the Mo and Si, respectively. The reflectivity is a resonant property of the reflective ML coating **220**, such that the fields reflected by every pair of layers interfere constructively and add to the total reflection. The reflectivition occurs through the depth of the film, and any deformation or disruption of the layer structure within the reflective ML film **220** can become a defect.

Two types of defects that commonly occur in a EUV mask are shown in FIG. **2**. Defect **228** is formed in a reflective multiplayer (ML) film **220** and defect **226** occurs at a substrate **210**, which exhibit in form **232** of a protruded shape (bump) and a recessed shape (pit), respectively. The form **232** of the defects denotes a protruded defect **232** or a recessed defect **234**.

In the case of the protruded defect, the surface of the reflective ML film **220** in FIG. **2** is partially bulged. An extrinsic defect is a deformation or disruption of the reflective ML film **220** and the substrate **210** derive from an external perturbation, for example, defect **228**. The defects may be a particle imbedded in the reflective ML film **220** and the substrate **210** during the deposition process, or a particle, pit or scratch imbedded on the top of the coating after deposition. The effect of the defect on the reflected field will depend on where the defect is derived. When the nucleation occurs at the substrate **210**, or in the bottom part of the reflective ML film **220**, then the film growth dynamics will tend to damp out the structural perturbation. The defect may also be derived near or at the top of the reflective ML film **220**. This could be a particle introduced during the deposition of the top layers, or a particle, pit or scratch imbedded in the top surface subsequent to the deposition. The particle and the damaged part of the reflective ML film will shadow the underlying layers and thereby attenuate the reflected field.

Defects that are categorized into an intrinsic type may occur in the EUV mask. The intrinsic defect is derived from the statistical fluctuations that are characteristic of the vapor deposition process that is used to deposit the reflective ML film **220**. In particular, shot noise in the atom-by-atom deposition process leads to the accumulation of random roughness. The variance of the roughness scales fairly linearly with the total thickness of the reflective ML film **220**. The lower frequency components of the roughness are replicated by overlying layers and thereby propagate up towards the top of the coating. When one of these random thickness fluctuations exceeds a critical size that is approximately 0.5 nm in height and 100 nm in width, it becomes an intrinsic defect. The resulting deformation of the layer structure produces an unacceptable perturbation in the phase of the reflected field. Either the extrinsic- or intrinsic-type defects produce a modulation of the phase of the reflected field, and thus are both considered as phase defects.

FIG. **3**A is prospective view schematically illustrating an EUV mask having a columnar reflector **350** according to various embodiments of the present disclosure. The EUV mask includes a substrate **310**, a reflective multilayer (ML) coating **320** for reflecting EUV light, a buffer layer **330**, an absorber pattern **340**, and a columnar reflector **350**. According to embodiments of the present disclosure, the absorber pattern **340** has features which may expose a top surface of the reflective ML coating **320**, or the buffer layer **330** and the columnar **350** is located on the top surface of the reflective ML coating exposed from the portion of the absorber pattern.

FIG. **3**B is a schematic cross-sectional view of the EUV mask of FIG. **3**A along line AA. According to various embodiments, the reflective ML coating **320** consists of pairs of molybdenum (Mo) layer **222** and amorphous silicon (Si) layer **324**. The thickness of the individual layer of the reflective ML coating **320** are about 3 and 4 nm for the Mo and Si, respectively. The reflectivity is a resonant property of the reflective Ml coating **320**, such that the fields reflected by every pair of layers interfere constructively. The reflectivity occurs through the depth of the film, and any deformation or disruption of the layer structure within the reflective coating can become a defect. A defect particle **326** is embedded in the

reflective ML film **320** exhibiting in form **328** of a protruded shape. The surface of the reflective ML coating **320** over the defect particle **326** in FIG. **3**B may be partially bulged. In some embodiments, the bulged part from the reflective ML coating **320** is leveled prior to the formation of the buffer layer **320** and the columnar reflector **350**. In some embodiments, the buffer layer **330** acts as a capping layer that is protective to the underlying reflective ML coating **320**.

The profile of deposited film may have an influence on the performance of reflected light. FIG. **3**C is a schematic cross-sectional view of the EUV mask according to alternative embodiments of FIG. **3**B. In various embodiments, because the buffer layer **330** is protruded with the defect form **328**, the subsequently-deposited columnar reflector **350** may have a Gaussian or curving shape along the surface of the buffer layer **330**. Alternatively, referring to FIG. **3**D, the columnar reflector **350**, which has a top surface in V-shape, may be deposited on the protruded surface of the buffer layer **330** and the defect form **328**. In some embodiments, the top surface may be in arbitrary form as long as in favor of the performances of the reflected light. According to various embodiments of the present disclosure, the columnar reflector **350** has a cross-sectional area substantially equal to the form **328** of the shift defect in the reflective ML coating **320** underneath the columnar reflector **350**. In various embodiments, the cross-section area of the columnar reflector **350** is arbitrary such as in a Gaussian, rectangle, square, circular, polygonal or curving shape. In some embodiments, the columnar reflector **350** is not in contact with a sidewall of the absorber pattern **340**.

According to various embodiments of the present disclosure, the columnar reflector **350** has one or more stack of alternating layers of a high index of refraction material **352** and a low index of refraction material **354**. In some embodiments, the columnar reflector **350** has one or more stack of alternating layers of three layers of two low index of refraction material **354** and one high index of refraction material **352** or one low index of refraction material **354** and two high index of refraction material **352**.

In certain embodiments, the low index of refraction material **354** is Si, TEOS, B4C, SiO_2, Y, or SiC, and the high index of refraction material **352** is Mo, MoO_2, Cr, W, La, Mg, Ru, or TaBN. In an embodiment, the low index of refraction material **352** is TEOS and the high index of refraction material **354** is Cr.

As shown in FIG. **4**E, there exist a gap d between the columnar reflector **450** and the absorber pattern **442**. In various embodiments, the gap d may be intentionally introduced to increase the intensity of reflected light by revealing more normal reflective multilayer surfaces; that is, the surfaces have no defects underneath. Basically, the dimension of the gap d has to be large enough to guarantee the critical dimension (CD) error of post-repair features/regions within −/+10% variation of a layout designed target.

During the EUV lithography process, up to about 40% of the UN light is absorbed by the EUV mask. Thermal expansion caused by the heating leads to a large image distortion that may exceed the error tolerance. Low thermal expansion material (LTEM) has been used as the substrate material for the substrate of the EUV masks. Accordingly, the substrate **310** may has a low thermal expansion coefficient (for example, the thermal expansion coefficient within a temperature range of from 19° C. to 27° C. is $0\pm1.0\times10^{-7}$/° C. In various embodiments, the thermal expansion coefficient is $0\pm0.3\times10^{-7}$/° C., $0\pm0.2\times10^{-7}$/° C., $0\pm0.1\times10^{-7}$/° C., or $0\pm0.05\times10^{-7}$/° C. As the substrate **310**, a glass having a low thermal expansion coefficient, such as a β quartz may be used, but the substrate is not so limited.

The reflective ML coating **320** of the EUV mask has a high EUV light reflectance. The selection of materials in the reflective ML coating **320** depends on the radiation wavelength (λ), in which each layer has a thickness of approximately one quarter of λ. In particular, the thickness of the respective layers of the reflective ML coating **320** depends on the radiation wavelength λ, and the incidence angle of the radiation light. For EUV, the λ is 13.5 nm and the incidence angle is about 5-6 degrees. The maximum reflectance to light having a wavelength in the vicinity of 13.5 nm is at least 60%. The thicknesses of the alternating layers are tuned to maximize the constructive interference of the EUV light reflected at each interface and to minimize the overall absorption of the EUV light. The reflective ML coating **320** can achieve about 60-75% reflectivity at the peak radiation wavelength. In various embodiments, the reflective ML coating **320** has about 30 pairs to 60 pairs of alternating layers of a high index of refraction material **322** and a low index of refraction material **324**. For example, 40 pairs of the alternative layers **322**/**324** of the reflective ML coating **320** are deposited in which the high index of refraction material **322** may be formed from about 2.8 nm thick Molybdenum (Mo) while the low index of refraction material **324** may be formed from about 4.1 nm thick Silicon (Si).

The buffer layer acting as a capping layer may be made of is made of carbon (C), silicon carbide (SiC), silicon (Si), or Ruthenium (Ru). For example, the capping layer of about 2.5 nm thick Ruthenium (Ru) may be formed at the top of the reflective ML coating **320** to prevent oxidation of Molybdenum by exposure to the environment. The Ru capping layer is likely to be oxidized in a step to be carried out during production of a mask or in a step to be carried out at the time of producing a photomask from the mask (such as a cleaning, defect inspection, heating, dry etching or defect correcting step).

FIGS. **4**A-E are schematic cross-sectional views at various stages of a method fabricating an EUV mask according to various embodiments of the present disclosure. The method is able to locally repair all types of aforementioned defects, so as to reduce deleterious effects of the defects on the projected pattern in the photoresist according to various embodiments of the present disclosure. For reasons of simplicity, FIGS. **4**A-**4**E may only illustrate a part of the EUV mask.

In FIG. **4**A, a substrate **410** with a low defect level and a smooth surface is used as the starting material for the EUV mask **200** in the present disclosure. The substrate **410** has a low coefficient of thermal expansion (CTE). in some embodiments, the substrate **410** is a glass or glass-ceramic material. For example, the substrate **410** may be formed of β-quartz.

Referring to FIG. **4**B, a reflective ML coating **420** is formed over the substrate **410**. The reflective ML coating **420** has about 30-60 pairs of alternating layers of a high index of refraction material **422** and a low index of refraction material **424**. In some embodiments, the reflective ML coating **320** has 40 pairs of the alternative layers **422**/**424**. A high index of refraction material **422** includes elements with high atomic number which tend to scatter EUV light. A low index of refraction material **424** includes elements with low atomic number which tend to transmit. EUV light. The reflective ML coating **420** is formed over the substrate **410** by using ion beam deposition (IBD) or DC magnetron sputtering. The thickness uniformity should be better than 0.8% across the substrate **3410**. IBD results in less perturbation and fewer defects in the upper surface of the reflective ML coating **420** because the deposition conditions can usually be optimized to

smooth over any defect on the substrate **410**. In various embodiments, 40 pairs of the alternative layers **422**/**424** of the ML coating **420** are deposited in which the high index of refraction material **422** may be formed from about 3 nm thick Mo while the low index of refraction material **424** may be formed from about 4 nm thick Si. For example, the high index of refraction material **422** may be formed from about 2.8 nm thick Mo while the low index of refraction material **424** may be formed from about 4.1 nm thick Si.

In various embodiments, in fabricating an EUV mask, a substrate **410** may be provided having the reflective ML coating **420** thereon. in this case of the substrate **410** already having the reflective ML coating **420**, the operation in FIG. **4**B may be omitted in the method of fabricating the EUV mask according to the embodiments of the present disclosure.

As shown in FIG. **4**C, a buffer layer **430** is formed over the reflective ML coating **420**. The buffer layer **430** may have a thickness of about 20-60 nm. In various embodiments, the buffer layer may a Ru capping layer formed at the top of the ML coating **420** to prevent oxidation of Mo by exposure to the environment, in some embodiments, the buffer layer may be formed from silicon dioxide (SiO_2) or a silicon (Si) layer. The buffer layer **430** may be low temperature oxide (LTO) as SiO_2, or other materials, such as silicon oxynitride (SiOxNy) or carbon (C). The buffer layer **430** may act later as an etch stop layer for patterning of the overlying absorber layer **440** formed in the following operation. An absorber layer **440** is formed over the buffer layer **430** according to various embodiments of the present disclosure. In embodiments, the absorber layer **440** has a total thickness d raging from 30-70 nm. The absorber layer **340** may be deposited by RF sputtering, DC sputtering, ion beam deposition (IBD) or atomic layer chemical vapor deposition (ALD).

Referring to FIG. **4**D, the absorber layer **440** is patterned to be an absorber pattern **442** having features thereon and exposing at least a portion of a top surface of the underlying buffer layer **430**, or the reflective ML coating **420** in the absence of the buffer layer **430**. Patterning the absorber layer **440** includes forming a photoresist pattern over the absorber layer **440** in an absorption region, etching the absorber layer **440** by using the photoresist pattern as an etch mask to form an absorber pattern, and removing the photoresist pattern. In particular, the absorber layer **440** may be covered with a radiation-sensitive layer, such as photoresist, that is coated, exposed, and developed with a desired pattern. The photoresist pattern has a thickness of about 160-640 nm. As desired, a chemically-amplified resist (CAR) may be used. Depending on the photoresist pattern used, exposure is performed on an electron beam (e-beam) writer or a laser writer. After post-develop measurement of the CD of the features in the photoresist pattern, the pattern is transferred into the absorber pattern **442** as shown in FIG. **4**D. Reactive ion etch may be used. For example, an absorber layer **440** may be dry etched with a gas which contains chlorine, such as Cl_2 or BCl_3, or with a gas which contains fluorine, such as NF_3. Argon (Ar) may be used as a carrier gas. In some cases, oxygen (O_2) may also be included as carrier. The etch rate and the etch selectivity depend on the etchant gas, etchant flow rate, power, pressure, and substrate temperature. The buffer layer **430** may serve as an etch stop layer to help achieve a good etch profile in the overlying absorber layer **440**. The buffer layer **430** protects the underlying reflective ML coating **420** from damage during etch of the absorber layer **440**.

Referring to FIG. **4**E, a columnar reflector **450** is deposited between the absorber pattern **442** by a suitable process. In other words, the columnar reflector **450** is deposited between the features of the absorber pattern **442**, as shown in FIG. **3**B or **4**E. In various embodiments, the columnar reflector **450** is formed by alternatively depositing a first layer of a low index of refraction material, and depositing a second layer of a high index of refraction material for at least one time. In some embodiments, the columnar reflector **450** is formed by alternatively depositing a first layer of a low index of refraction material, depositing a second layer of a low or a high index of refraction material, and depositing a third layer of a high index of refraction material for at least one time. In some embodiments, the high index of refraction material **452** is Mo, MoO_2, Cr, W, La, Mg, Ru, or TaBN and a low index of refraction material **454** is Si, TEOS, B4C, SiO_2, Y, or SiC. In certain embodiments, the low index of refraction material **454** is TEOS and the high index of refraction material **452** is Cr. In some embodiments, the bulged part from the reflective ML coating **420** is leveled prior to the formation of the buffer layer **420** and the columnar reflector **450**. According to various embodiments, the cross-section area of the columnar reflector is in a Gaussian, rectangle, square, circular, polygonal or curving shape. In some embodiments, the columnar reflector **450** is not in contact with a sidewall of the absorber pattern **442**.

FIG. **5** is a flowchart **500** illustrating a method of fabricating an EUV mask according to various embodiments of the present disclosure. The operations **502**-**506** are disclosed in association with the cross-sectional side views of a portion of the EUV mask **200** from FIGS. **4**A to **4**E at various fabrication stages.

In operation **502**, a substrate **410** is provided having a reflective ML coating on the substrate and an absorber pattern over the reflective ML coating. Referring to FIG. **4**A, the substrate **410** is made of a material having a low coefficient of thermal expansion (CTE). For example, the substrate **410** may be formed of β-quartz.

Still referring to the operation **502**, a reflective ML coating **420** is deposited over the substrate **410**. In FIG. **4**B, the reflective ML coating **420** has about 30-60 pairs of alternating layers of a high index of refraction material **422** and a low index of refraction material **424**. In embodiments, the reflective ML coating **420** has 40 pairs of the alternative layers **422**/**424**. As various embodiments, in fabricating an EUV mask, a substrate **410** may be provided having the reflective ML coating **420** thereon. In this case of the substrate **410** already provided with a reflective ML coating **420** on the substrate, a buffer layer **430** (optional) and the absorber pattern **440**, the operation **502** in FIG. **5** may refer to the stage of FIG. **4**D in the method of fabricating the EUV mask according to the embodiments of the present disclosure.

Referring to operation **504** of FIG. **5**, areas between the absorber pattern (i.e., on the top surface of the reflective ML coating **420** or the buffer layer **430**) is inspected for defects. In some embodiments, inspecting for the defects on the top surface of the reflective ML coating is conducted by atomic force microscope (AFM) scanning.

Referring to operation **506** of FIG. **5**, if a defect is found, a columnar reflector **450** of FIG. **4**E is deposited right above the defect, as shown in FIG. **3**B. In various embodiments, the columnar reflector **450** may be deposited through the following operations. Referring to FIG. **6**, in operation **602**, the defect is scanned with the AFM to determine an area of the defect through information provided from the AFM scanning For example, the coated substrate may be mounted on a moveable stage in a vacuum chamber of an electron beam (e-beam) system; the area of the defect, which is closed to an e-beam is positioned by navigating the moveable stage. In operation **604**, the area of the defect is scanned with an e-beam to define an excess portion, if any, of the absorber

pattern through the information provided from the AFM. For example, the etching gas may be directed concurrently with the e-beam so as to the defect to etch the excess portion. In operation **606**, an etching gas is directed to the area of the defect to etch the excess portion of the absorber pattern. For example, the depositing gas may be directed concurrently with the e-beam so as to deposit a columnar reflector right above defect. Further, a deposition gas is directed in operation **608** to deposit the columnar reflector right above the area of the defect. In various embodiments, the cross section of the area of the defect is in Gaussian, rectangle, square, circular, polygonal or curving shape.

Additionally, an feature of the area where the reflector **405** is deposited is compared with the CD error or aerial image to check if the CD error of the feature of the area variation is within −/+10% variation of a layout designed target (i.e. a wafer dimension).

According to various embodiments of the present disclosure, the columnar reflector **450** has a cross-sectional area substantially equal to the defect in the reflective ML coating **420** underneath the columnar reflector **450**. In various embodiments, the cross-section area of the columnar reflector **450** is in a Gaussian, rectangle, square, circular, polygonal or curving shape. In some embodiments, the columnar reflector **450** has a gap with and is not in contact with a sidewall of the absorber pattern **440**. In specific embodiments, in case the defect is larger than the space between the absorber pattern between which the columnar reflector **450** can be deposited, the patterned absorber layer **440** may need to be trimmed to fully expose the defect from the top surface of the reflective ML coating **420** or the buffer layer **430**. Trimming of the patterned absorber layer **440** leaves sufficient space for depositing the columnar reflector **450** without contacting the sidewall of the patterned absorber layer **440**. In various embodiments, depositing the columnar reflector is conducted with suitable process such as an e-beam, ion-beam or laser-beam process. Trimming the absorber pattern may also be conducted with the e-beam, ion-beam or laser-beam process.

In order to compensate the EUV phase defect, a columnar reflector, which acts as a Bragg reflector, is deposited according to various embodiments to locally compensate and repair the EUV phase defect. According to the embodiments of the present disclosure, the reflective loss due to the EUV phase defect can be compensated and recover the phase different due to the EUV phase defect, so as to form a desirable wafer printed image.

The foregoing has outlined features of several embodiments so that those skilled in the art may better understand the detailed description that follows. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions and alterations herein without departing from the spirit and scope of the present disclosure.

What is claimed is:

1. An extreme ultraviolet (EUV) mask, comprising:
- a substrate,
- a reflective multiplayer (ML) coating on the substrate,
- an absorber pattern over the reflective ML coating; and
- a columnar reflector between sidewalls of the absorber pattern, the columnar reflector having at least one stack of alternating layers of a low index of refraction material and a high index of refraction material, or of three layers of two low index of refraction materials and one high index of refraction material or one low index of refraction material and two high index of refraction materials.

2. The EUV mask of claim **1**, further comprising a buffer layer, wherein the buffer layer acts as a capping layer between the absorber pattern and the reflective ML coating.

3. The EUV mask of claim **2**, wherein the buffer layer is made of carbon (C), silicon carbide (SiC), silicon (Si), or Ruthenium (Ru).

4. The EUV mask of claim **1**, wherein the columnar reflector has a cross-sectional area substantially equal in size to a shift defect that is in the reflective ML coating or the substrate, and is underneath the columnar reflector.

5. The EUV mask of claim **4**, wherein the cross-section area of the columnar reflector is in a Gaussian, rectangle, square, circular, polygonal or curving shape.

6. The EUV mask of claim **1**, wherein the low index of refraction material is Si, TEOS, B4C, SiO_2, Y, or SiC, and the high index of refraction material is Mo, MoO_2, Cr, W, La, Mg, Ru, or TaBN.

7. The EUV mask of claim **6**, wherein the stack of the columnar reflector is made of alternating layers of TEOS and Cr.

8. The EUV mask of claim **6**, wherein the columnar reflector has a top surface in V-shape.

9. The EUV mask of claim **1**, wherein the columnar reflector and at least one of the sidewalls of the absorber pattern do not contact each other.

10. The EUV mask of claim **1**, wherein the stack of the columnar reflector has a thickness of 7-10nm.

11. A method of manufacturing an extreme ultraviolet (EUV) mask, the method comprising:
- providing a substrate with a reflective multilayer (ML) coating on the substrate, and a absorber pattern over the reflective ML coating;
- inspecting for defects between sidewalls of the absorber pattern; and
- if a defect is found, depositing a columnar reflector right above the defect.

12. The method of manufacturing the EUV mask of claim **11**, wherein depositing the columnar reflector right above the defect further comprising:
- scanning the defect with Atomic Force Microscope (AFM) to determine an area of the defect through information from the AFM;
- scanning the area of the defect with an electron beam to define, if any, an excess portion of the absorber pattern through the information from the AFM;
- directing an etching gas to the area of the defect to etch the excess portion of the absorber pattern; and
- directing a deposition gas to deposit the columnar reflector right above the area of the defect.

13. The method of manufacturing the EUV mask of claim **11**, wherein depositing the columnar reflector is performed by alternatively depositing a first layer of a low index of refraction material, and depositing a second layer of a high index of refraction material for at least one time.

14. The method of manufacturing the EUV mask of claim **11**, wherein depositing the columnar reflector is performed by alternatively depositing a first layer of TEOS and depositing a second layer of Cr for at least one time.

15. The method of manufacturing the EUV mask of claim **11**, wherein depositing the columnar reflector is performed by alternatively depositing a first layer of a low index of refraction material, depositing a second layer of a low or a high index of refraction material, and depositing a third layer of a high index of refraction material for at least one time.

16. The method of manufacturing the EUV mask of claim 15, wherein the columnar reflector is not in contact with a side wall of the absorber pattern.

17. The method of manufacturing the EUV mask of claim 11, further comprising trimming the absorber pattern to fully expose the defect from a top surface of the reflective ML coating before depositing a columnar reflector right above the defect.

18. The method of manufacturing the EUV mask of claim 11, wherein inspecting for the defects on a top surface of the reflective ML coating is conducted by atomic force microscope (AFM) scanning.

19. The method of manufacturing the EUV mask of claim 11, wherein depositing the columnar reflector is conducted with an e-beam, ion-beam or laser-beam process.

20. The method of manufacturing the EUV mask of claim 11, wherein trimming the absorber pattern is conducted with an e-beam, ion-beam or laser-beam process.

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